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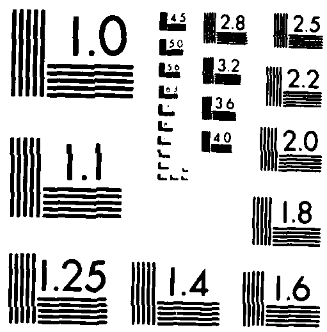

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

DEPARTMENT OF THE NAVY DTNSRDC

DESCRIPTION OF WAKE SURVEY RAKE CALIBRATION TECHNIQUE AND CALIBRATION RESULTS OF RAKE 4

by

Dennis R. Mullinix

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SHIP PERFORMANCE DEPARTMENT REPORT

MARCH 1985

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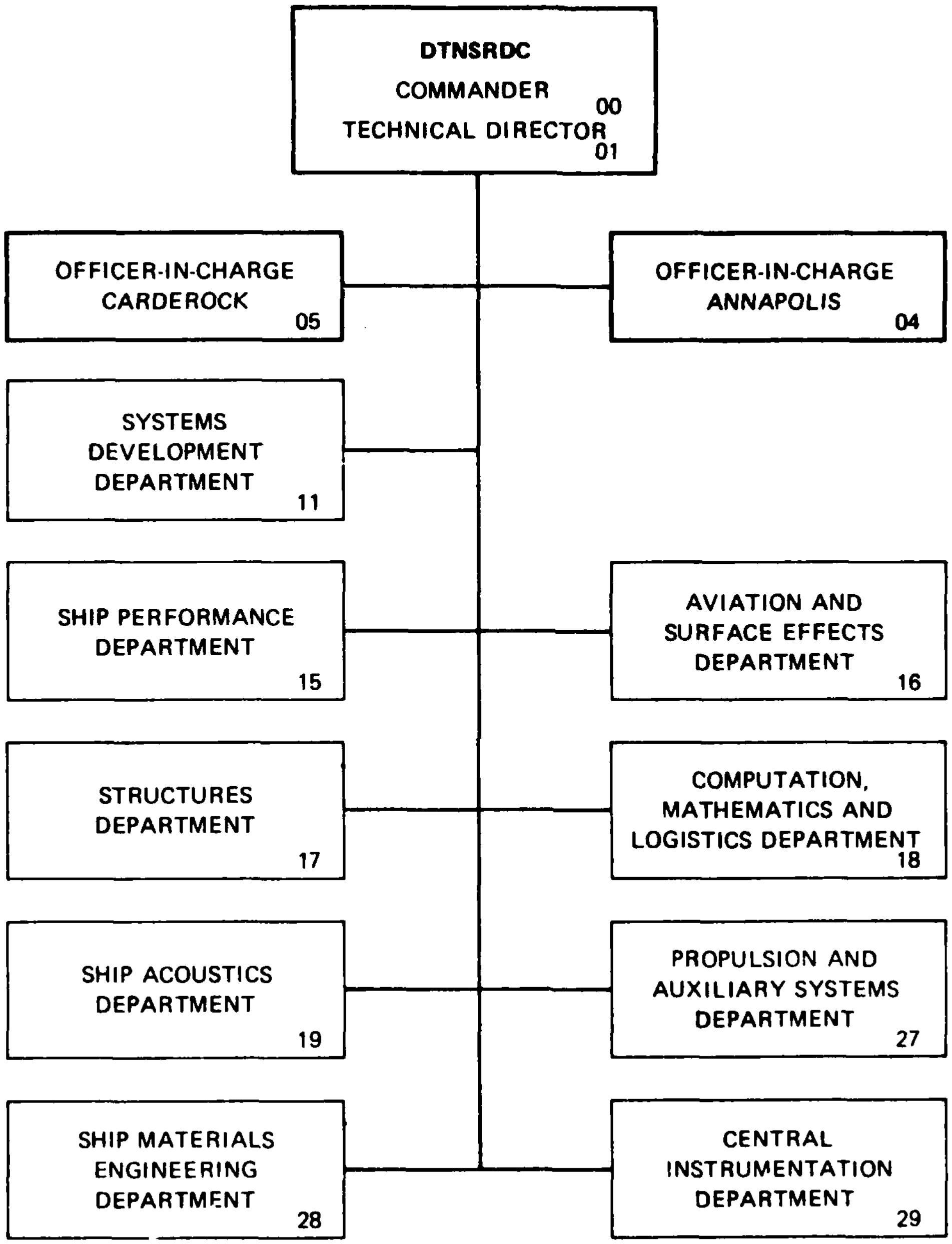

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This report describes the technique for performing a pitot tube rake calibration and presents the results of the calibration of Rake 4. Brief descriptions of the experimental apparatus and procedures are included. Results of the calibration of Rake 4 have been used for the wake survey experiment on the model of the ARS-50. Calibration coefficients for Rake 4 are documented in this report.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

C	Center Pitot Tube Hole Pressure
R1, R2	Outer Pitot Tube Hole Pressure in Radial Plane
T1, T2	Outer Pitot Tube Hole Pressure in Tangential Plane
V	Velocity
β	Flow Angle from the Pitot Tube Center Hole

ABSTRACT

This report describes the technique for performing a pitot tube rake calibration and presents the results of the calibration of Rake 4. Brief descriptions of the experimental apparatus and procedures are included. Results of the calibration of Rake 4 have been used for the wake survey experiment on the model of the ARS-50. Calibration coefficients for Rake 4 are documented in this report.

ADMINISTRATIVE INFORMATION

This work was authorized by the Naval Sea Systems Command (NAVSEA) by Work Request Number N00024-82. The David Taylor Naval Ship R&D Center (DTNSRDC) Work Unit Number was 1521-730.

INTRODUCTION

The David Taylor Naval Ship R&D Center (DTNSRDC) conducts wake surveys on models of surface ships and submarines on the towing carriages. The device used to measure the velocity field in way of the propeller disc of the model is called a pitot tube rake and is made up of several five-hole pitot tubes. The rake must be calibrated in open water before a wake survey experiment.

This report describes the complete rake calibration process including the apparatus, technique and computations and can be used as a reference for any future rake calibrations. The apparatus includes the rake calibration rig, the pressure transducers, the instrumentation, and the mini-computer used to collect the data. The experimental technique to calibrate rakes includes the alignment of the rake, the pressure gage procedures, and the data collection procedure. The computational procedures used to obtain the results from rake calibrations are found in the two appendixes. Appendix A gives the procedure for deriving velocity component ratios from pressure measurements. Appendix B gives the equations for the calibration constants.

This report also gives the description of Rake 4 and the results of the Rake 4 calibration. Rake 4 was built primarily for the wake survey experiment on the model for the ARS-50. These results are presented as calibration curves for the pitot tubes in Figures 7 through 14. The coefficients for these curves are presented in Table 1.

DESCRIPTION OF RAKE 4

Rake 4, shown in Figure 1, was built for use on the wake survey of the ARS-50. The rake had to be small because of the ducted propeller on the ARS-50. The four pitot tubes have hemispherical ends, each with five holes. Figure 2 shows the schematic of the five-hole pitot tube. The tubes are numbered one through four with tube one having the most inner radius. The odd tubes are on one side of the rake and the even tubes are on the other. The radii for the four tubes are 1.851 in. (47.02 mm), 2.426 in. (61.62 mm), 3.014 in. (76.55 mm), and 3.563 in. (90.5 mm).

EXPERIMENTAL APPARATUS

The rake calibration rig is the essential apparatus needed to calibrate a rake. Rake 4 is attached to the calibration equipment in Figure 3. This rig allows calibrations in the radial and tangential directions. The calibration is usually performed on Carriage I or Carriage II. The Rake 4 calibration was performed on Carriage II. Normally, the rake is calibrated in one plane, holding the other plane at 0° to the flow. There are graduated scales for both directions from -30° to +30° in 1° increments. The angle is changed by manually turning a wheel, but stepping motors and potentiometers have been added to the rig to improve the efficiency of the rake calibration. The stepping motors mechanically change the angle and the output from the potentiometers give the angle readings. These two additions to the calibration rig were added to set the angle, but not to be collected by the computer. During the Rake 4 calibration, both methods were used.

The rake calibration requires measuring the angle of the rake, the velocity of the towing carriage, and the pressures on the pitot tubes. The angle is determined by visually looking at the graduated scale and manually inputting the angle into the computer. The velocity of the carriage is measured and controlled by using a zero velocity pick up which provides a five volt square output pulse. For example, on Carriage II, there are 100 pulses/foot which permits regulations of carriage speed within a hundredth of a knot. These pulses are counted on an electronic counter controlled by the computer on the carriage. The pressure data are measured by using four Sensotec strain gage differential pressure transducers on a tube. The center hole (C) is connected to one side of all four pressure gages, then the other side of each gage is connected to

either R1, R2, T1 or T2. There are two sets of gages available; therefore, data can be collected from two tubes at the same time. A description of the use and calibration of five-hole pitot tubes is given in Hadler and Cheng[1], Hale and Norris[2], and Pien[3]. A block diagram of the instrumentation used with the pressure gages on the Rake 4 calibration is shown in Figure 4.

Data from the Rake 4 calibration were collected with a Model 70 Perkin-Elmer Mini-Computer. Figure 5 shows a diagram of the computer and its peripheral devices.

EXPERIMENTAL PROCEDURE

Alignment of the rake on the rig is critical. The radial differential pressures (R1 and R2) should be equal to each other and so should the tangential (T1 and T2) when the pitot tube is exactly aligned with the flow. If this is not the case, the physical zero will be shifted. This physical zero is the zero when the flow is exactly the same on each side of the Center hole. The pitot tubes on Rake 4 are not exactly parallel to each other; therefore, when the rake was aligned on the rig each tube was not exactly aligned with the flow. This misalignment caused a different zero shift with each pitot tube. These zero shifts can be seen in Figures 7-14.

The pressure gage system must be properly connected as shown in Figure 6. The valves are color coded to simplify bleeding, pressure gage calibration and experimental set up conditions. During the final bleeding process, the pressure gage system is attached to the rake allowing water to flow throughout the entire system. After switching the valves to the experimental condition, the experiment is ready to begin.

Collection of data for rake calibration is run at only one speed of the towing carriage. With Rake 4, the data were collected at 6 knots (3.09 m/s) on two tubes at a time, between ± 30° at 5° increments. Once the physical zero was established, data points were collected in 1° increments around zero, to better define the zero crossing. The measurements for each data point were taken and averaged over a period of five seconds. Measurements were also collected at duplicate angles to assure repeatability and accuracy. The pressure gage system can measure to within plus or minus two hundredths of an inch of water pressure (5 pascal).

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[1] References are listed on Page 6.

PRESENTATION OF RESULTS

Results of the Rake 4 calibration are presented in graphical form as a function of angle of inclination at one speed. The calibration curves consist of from 23 to 32 data points collected for each of the four pitot tubes in each of the two planes. Each data point on a curve consists of the value for the differential pressure ratio from which flow directions and magnitudes can be calculated for both the tangential and radial components. Appendix A presents the procedure for deriving velocity component ratios from pressure measurements.

The wake survey computer program requires the rake calibration to be in the form of coefficients created from the data points of each pitot tube. For this rake calibration, the coefficients were generated from the experimental data in the program POLYFIT. Appendix B explains the quantities which the coefficients represent on each of the Figures 7 through 14. POLYFIT fairs a curve through the data points by polynomial least squares. Using a fourth degree polynomial, the graphing program generated 80 intermediate points.

Figures 7 through 14 present the calibration curves for all pitot tubes on Rake 4 in the radial and tangential planes. The listing of coefficients for all the tubes are presented in Table 1 ready for input for a wake survey experiment.

DISCUSSION OF RESULTS

The Rake 4 calibration curves have the general shape of the previous calibration curves of other rakes, but with some different trends. Comparing the data is difficult because the tubes of Rake 4 are about one-quarter the length of the tubes of Rakes 6, 7 and 8. Rakes 6, 7 and 8 have spherical pitot tubes and Rake 4 has hemi-spherical pitot tubes. Previous rakes were built to closer tolerances than Rake 4.

As shown in Figures 7 through 14, the physical zero was not close to the assumed zero position. The zeroes of the radial plane for all four tubes were shifted to the positive direction by as much as 7°, i.e., the tubes were pointing away from the centerline of the rake. The figures for the tangential plane show that Tubes 1 and 3 were on the positive side by as much as 2°, and Tubes 2 and 4 were on the negative side by as much as 2°, all four tubes were pointing down. The nomenclature for positive and negative directions is shown in Figure 3.

SUMMARY AND RECOMMENDATIONS

Rake 4 was calibrated for use with the ARS-50 Wake Survey Experiment. This report briefly describes the rake calibration equipment and the rake calibration procedure. Results of Rake 4 calibration are presented in graphical form with coefficients of each curve.

Before these data were collected, there was some discussion about bending the tubes to get a better alignment. Due to scheduling and time constraints, this was not done for fear of breaking the tubes off the rake. Prior to further experiments, it is recommended that this rake be reconstructed and recalibrated.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of all Center personnel who contributed to the Rake 4 calibration experiment. Deserving of special recognition are Ms. Rae B. Hurwitz who assisted in the preparation of this report and Mr. Eugene E. West who set up the rake and helped to conduct the Rake 4 calibration experiment. Appreciation is expressed to Miss Evelyn I. Giesler for typing the manuscript of this report.

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2. Hale, M.R. and D.H. Norris, "The Analysis and Calibration of the Five-Hole Spherical Pitot Tube," ASME Paper 67-WA/FE-24, 8 pages, (1967).

3. Pien, P.C., "Five-Hole Spherical Pitot Tube," DTNSRDC Report 1229, (May 1958).

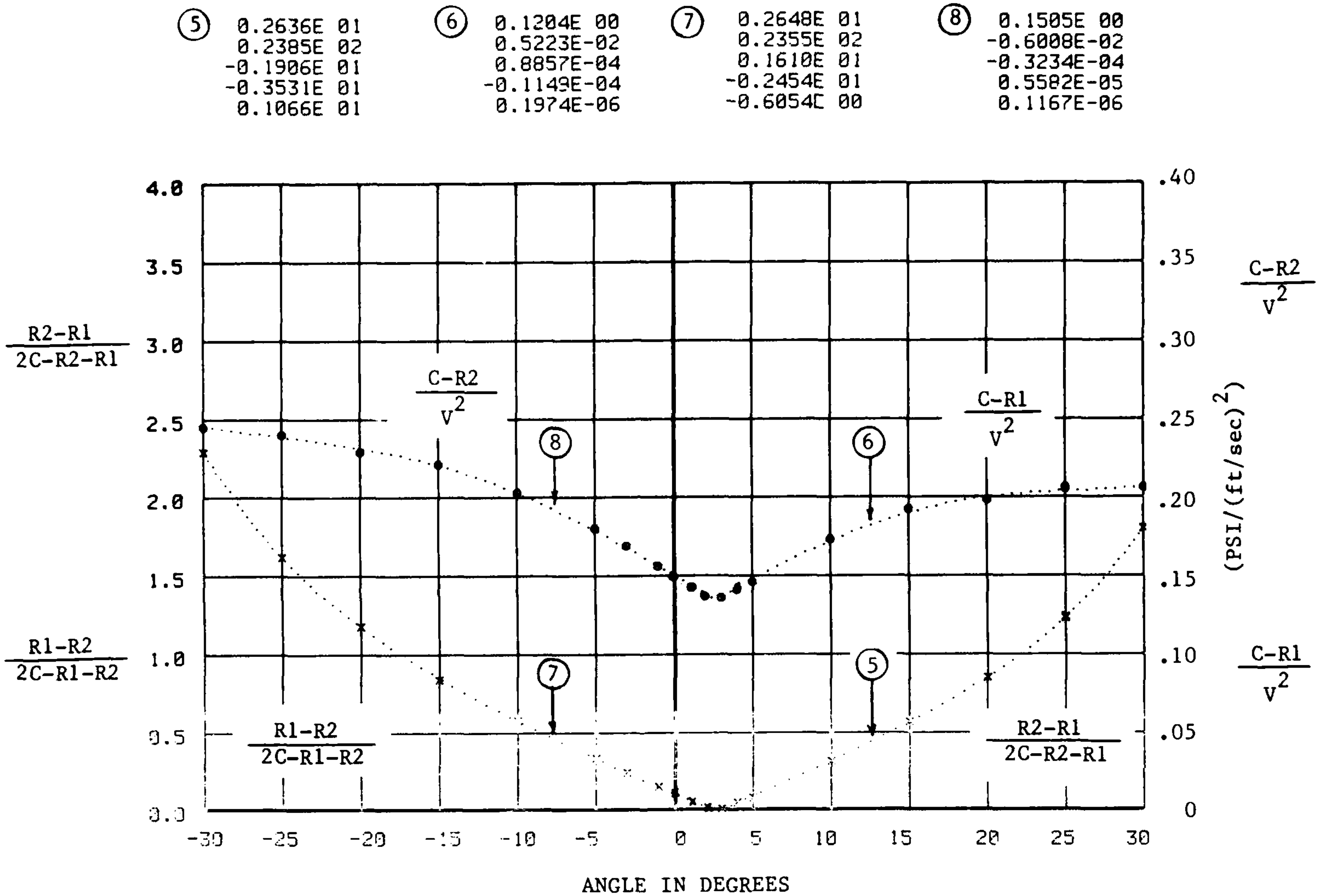

Figure 14 - Calibration of Tube 4 in Radial Plane

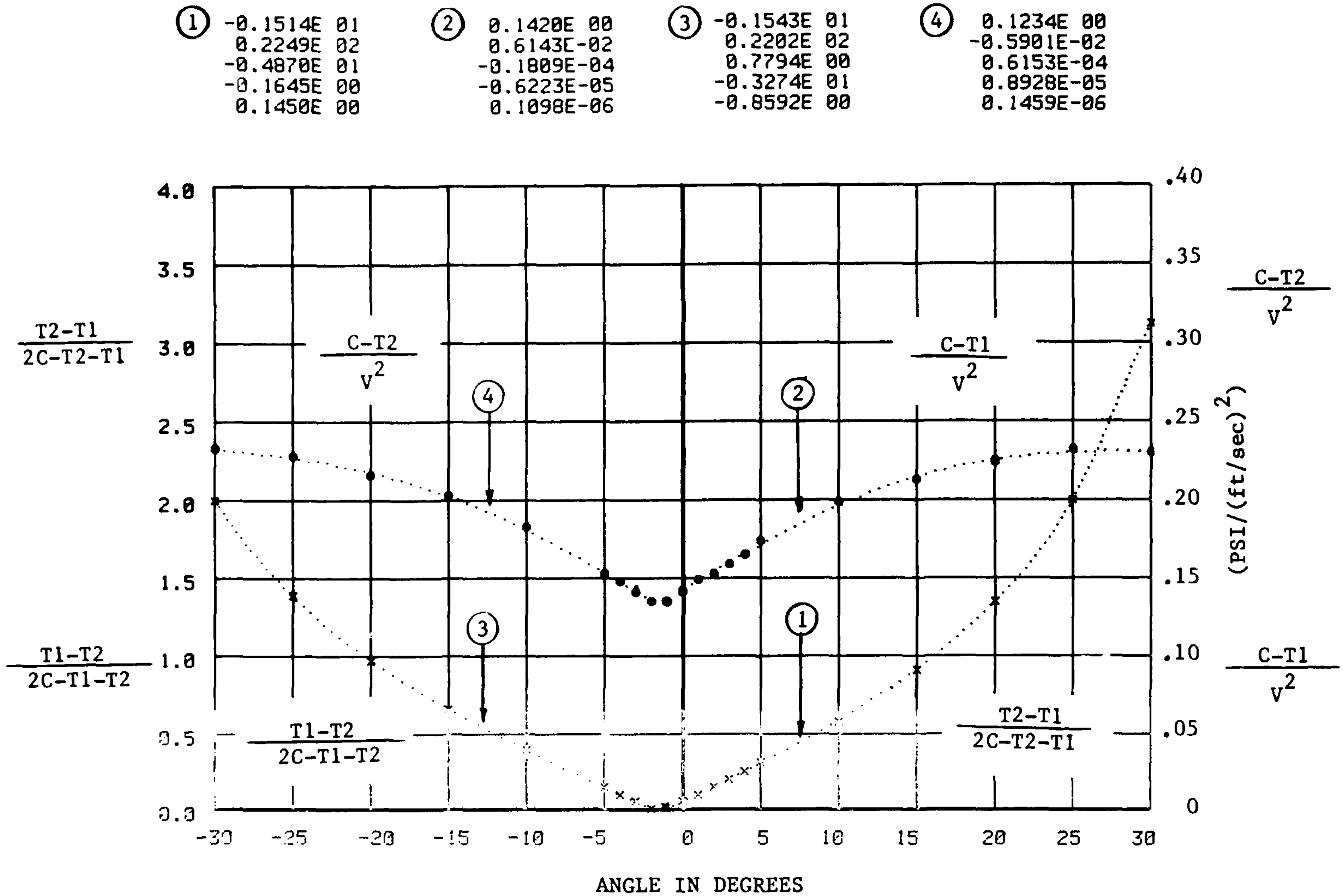

Figure 13 - Calibration of Tube 4 in Tangential Plane

5	6	7	8
0.5455E 01	0.9543E-01	0.5577E 01	0.1675E 00
0.2107E 02	0.7220E-02	0.2103E 02	-0.5648E-02
0.3473E 01	-0.6712E-05	-0.3469E 01	-0.8601E-04
-0.8224E 01	-0.9177E-05	-0.4932E 01	0.1032E-06
0.2414E 01	0.1713E-06	-0.9930E 00	-0.3659E-08

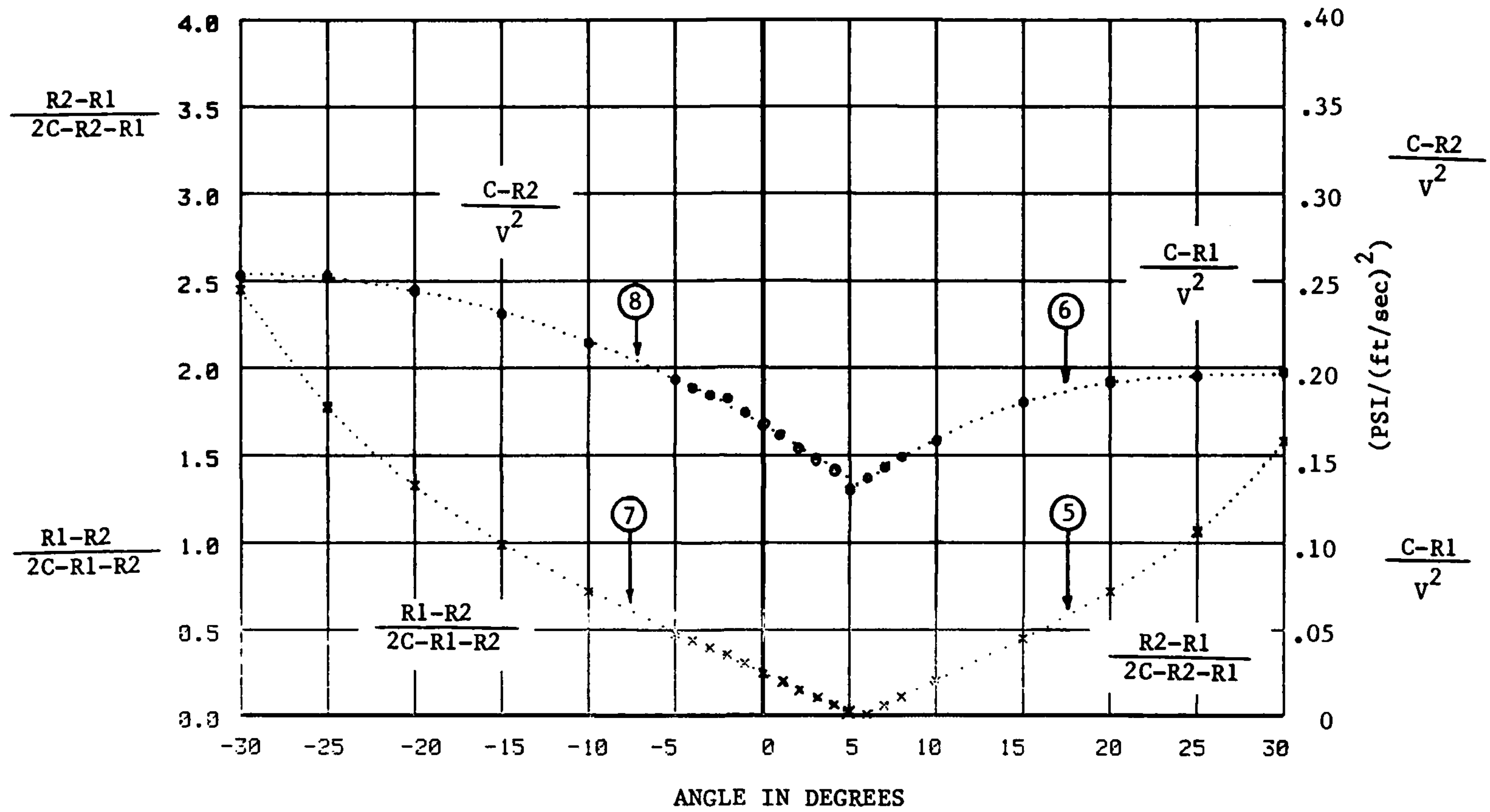

Figure 12 - Calibration of Tube 3 in Radial Plane

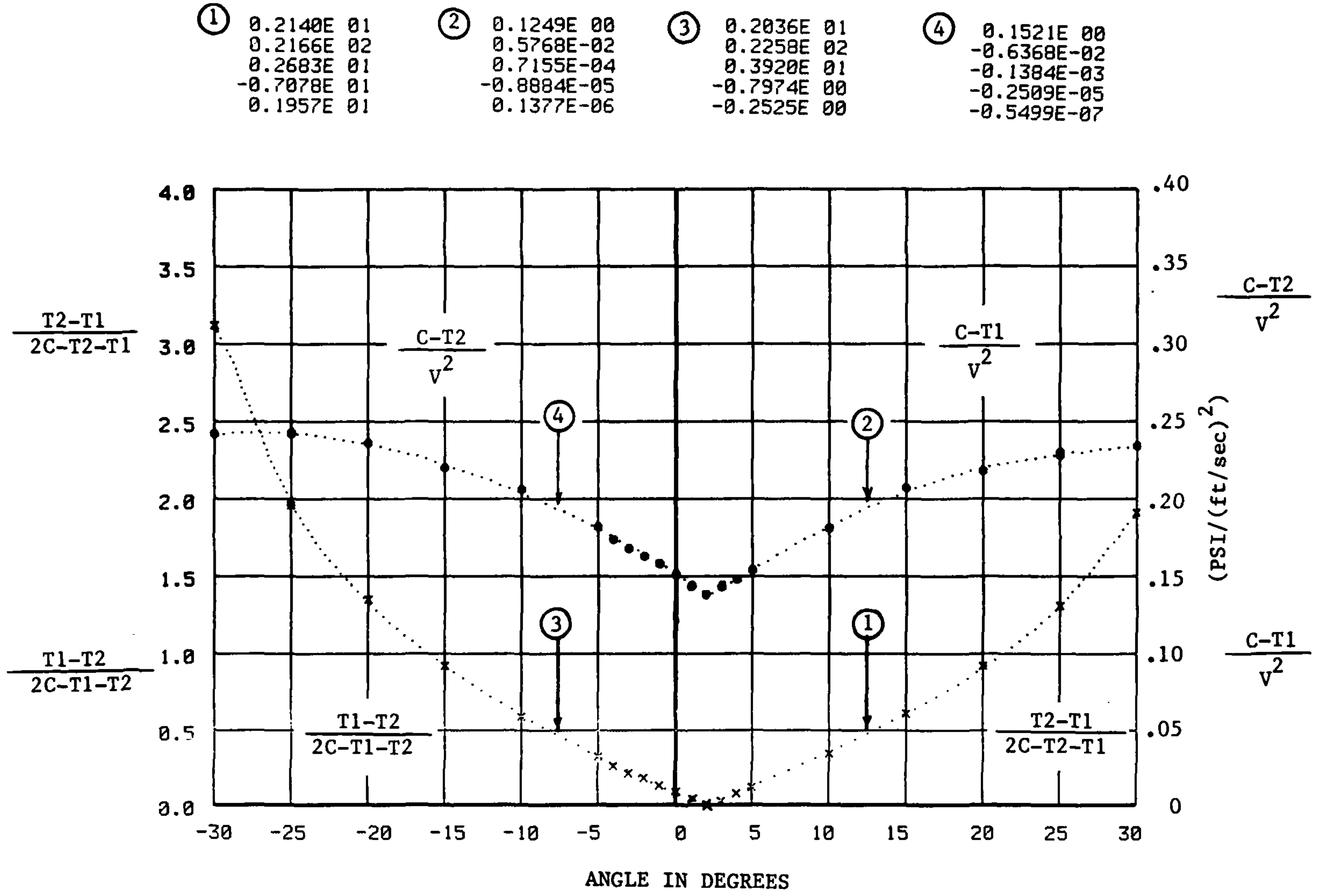

Figure 11 - Calibration of Tube 3 in Tangential Plane

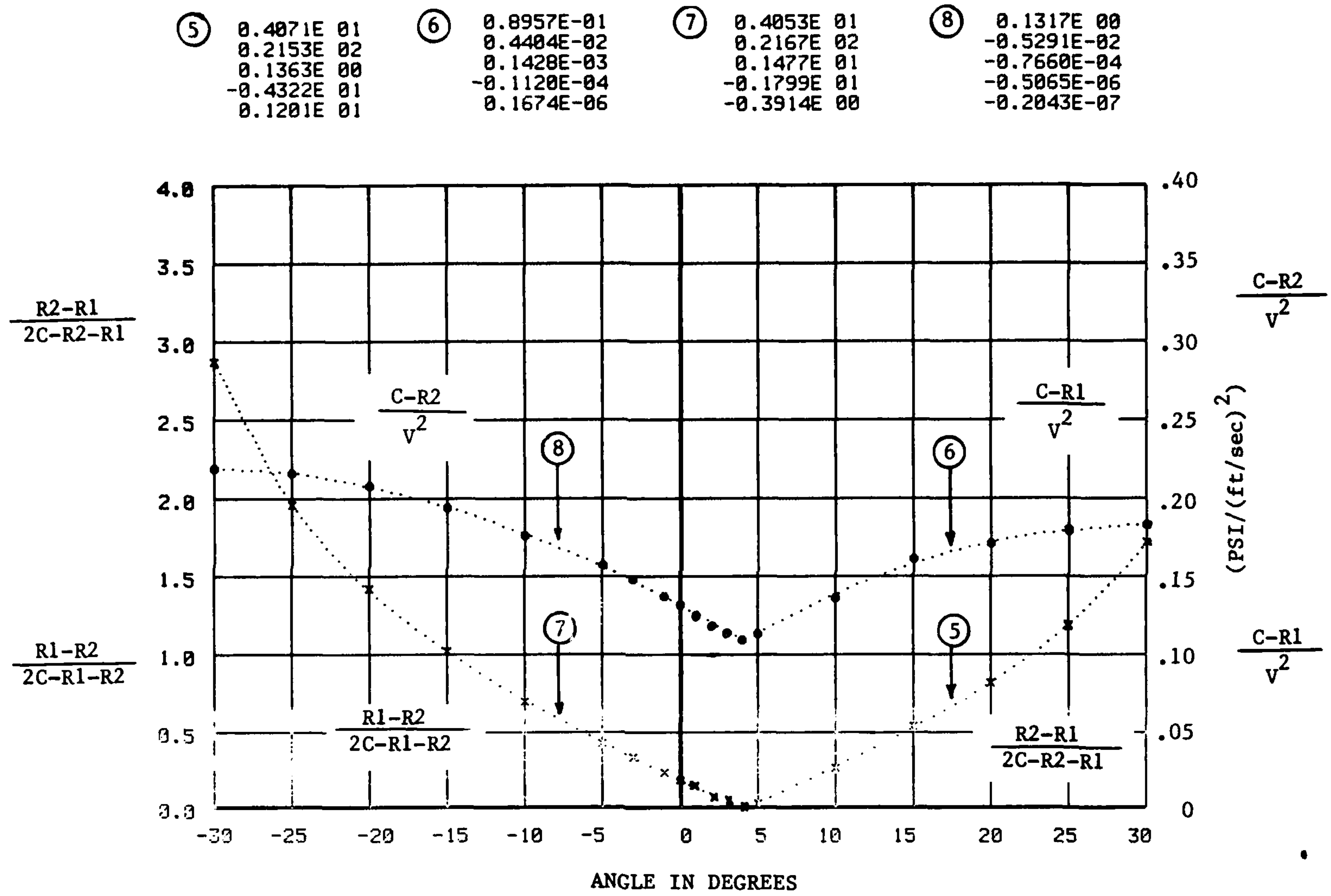

Figure 10 - Calibration of Tube 2 in Radial Plane

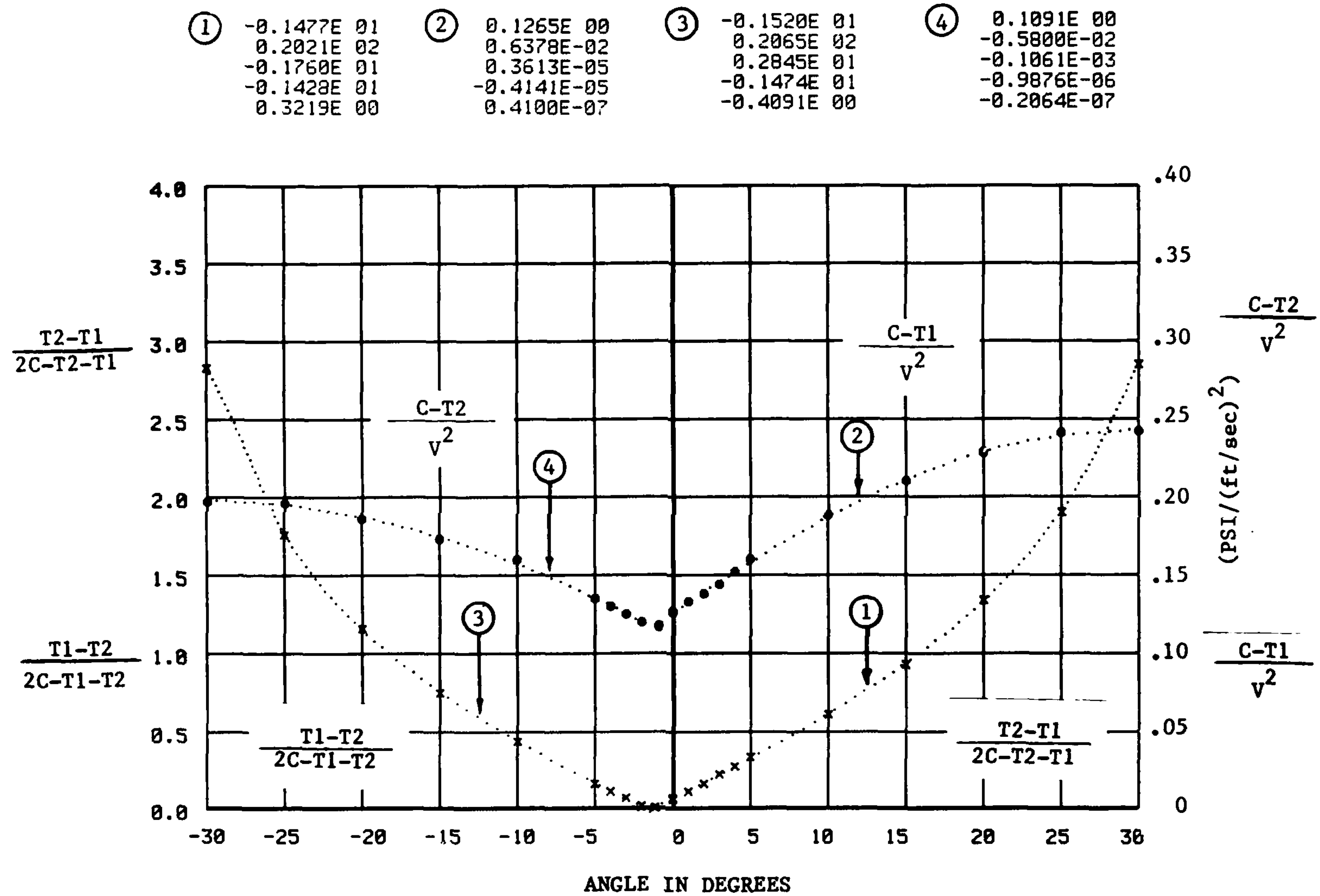

Figure 9 - Calibration of Tube 2 in Tangential Plane

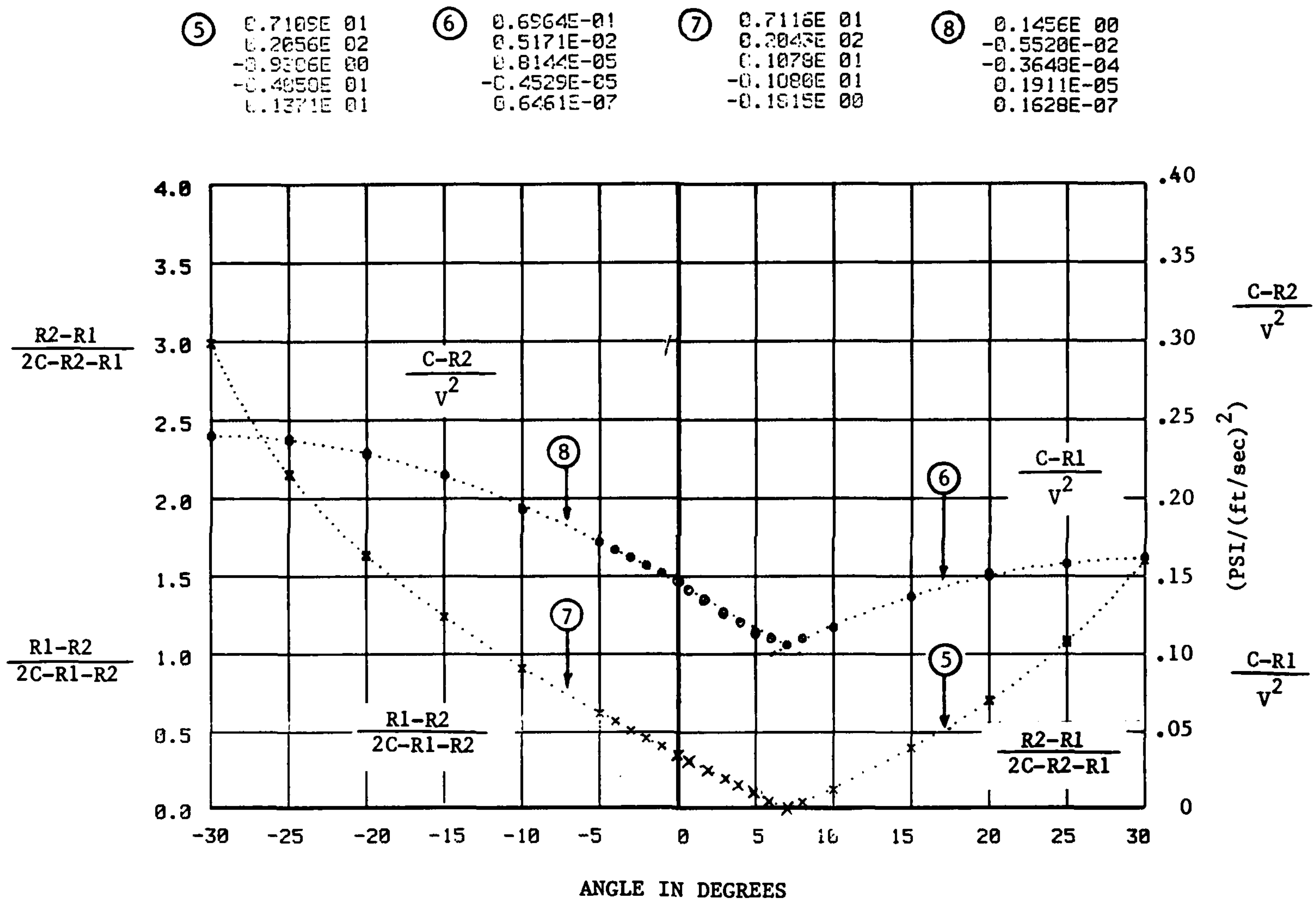

Figure 8 - Calibration of Tube 1 in Radial Plane

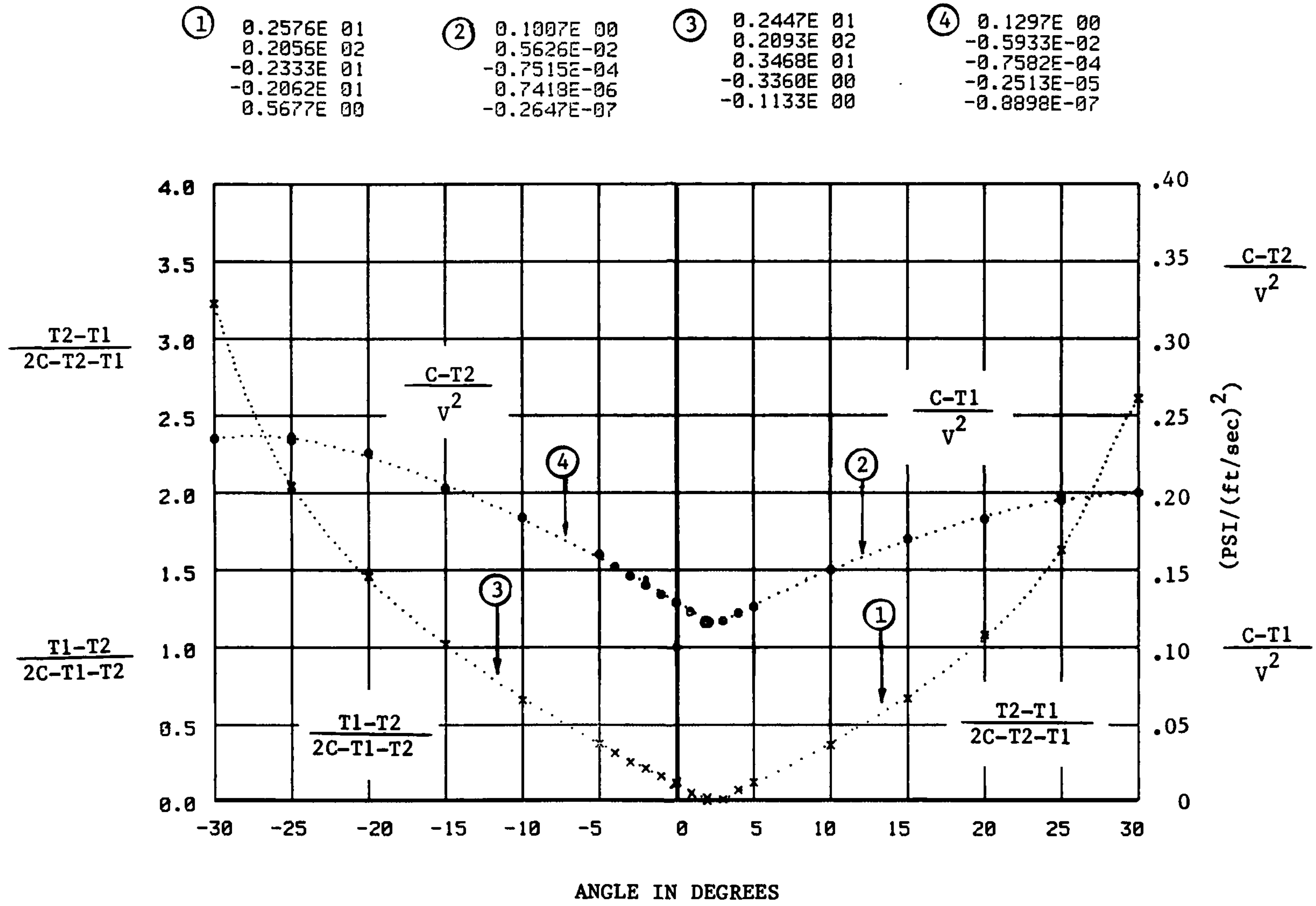

Figure 7 - Calibration of Tube 1 in Tangential Plane

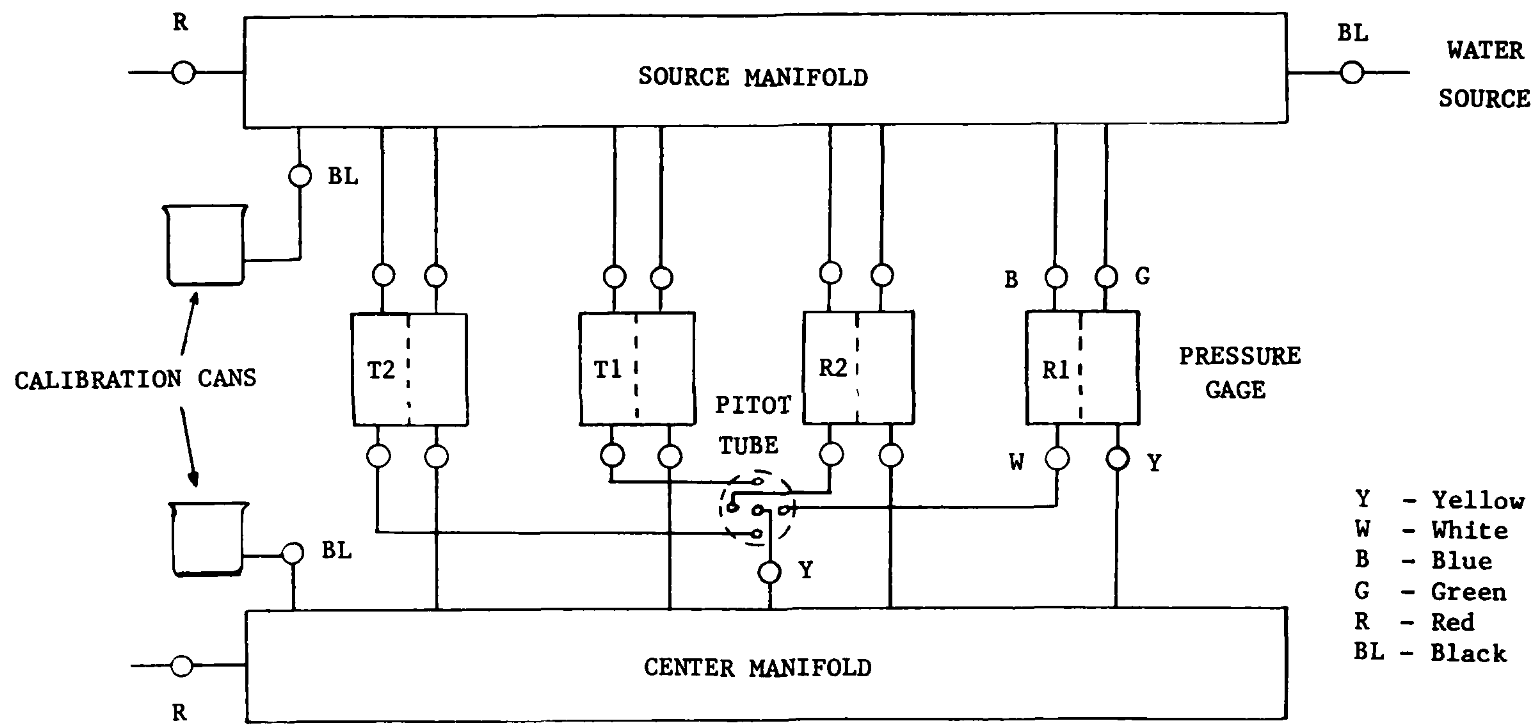

Figure 6 - Set-Up of Pressure Gage System

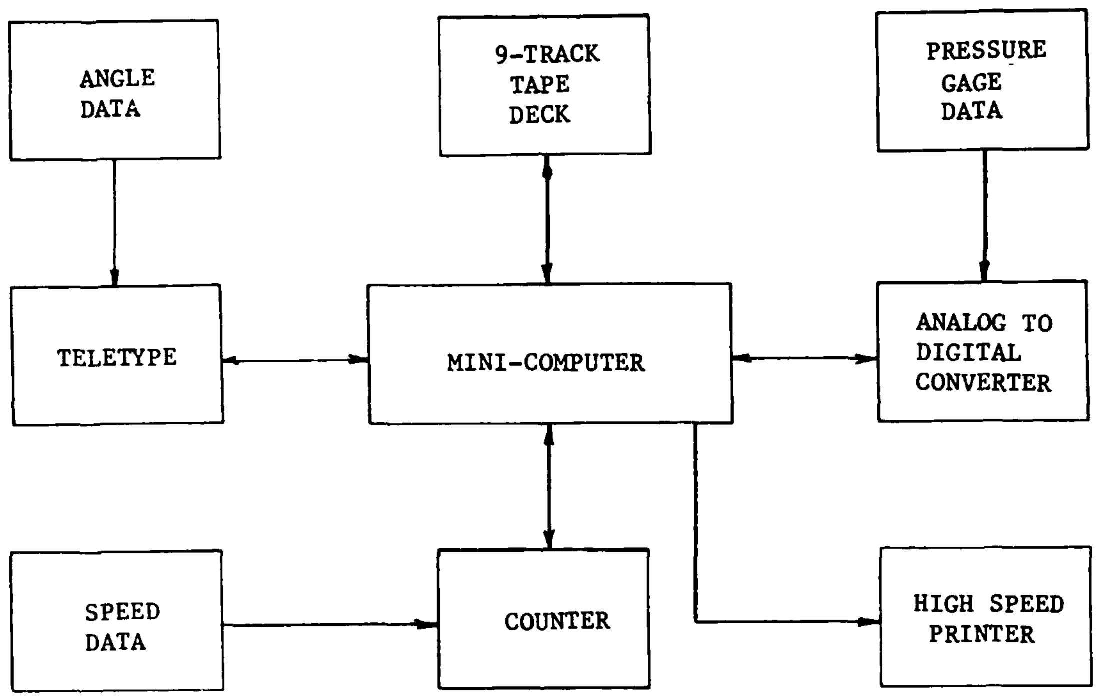

Figure 5 - Block Diagram of Mini-Computer and Peripheral Equipment

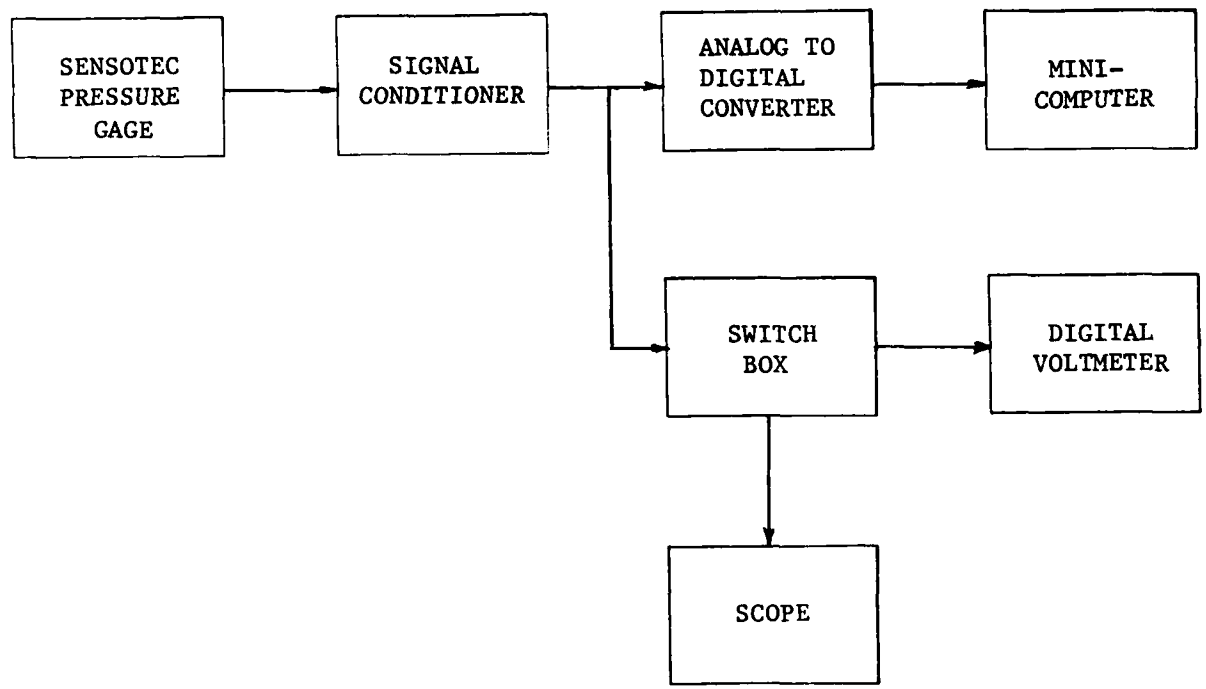

Figure 4 - Block Diagram of Pressure Gage Instrumentation

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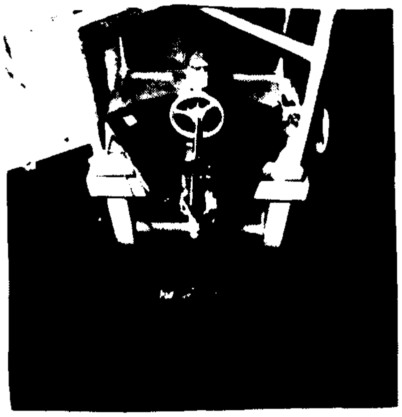

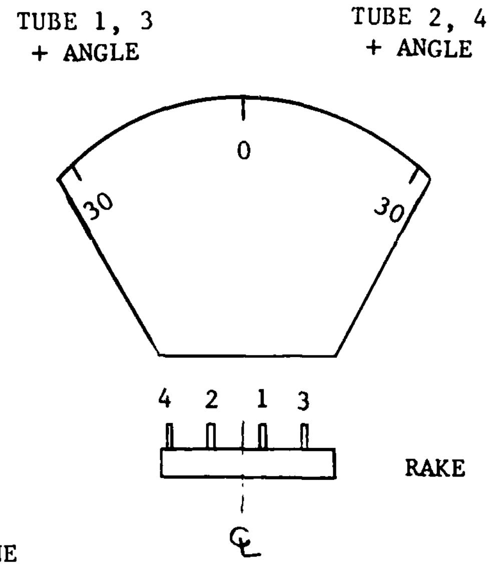

RADIAL PLANE

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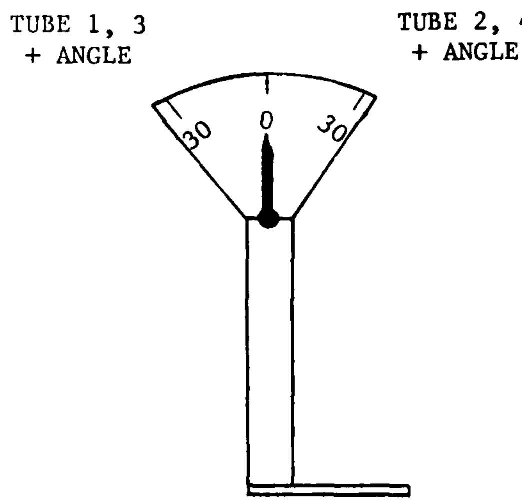

TANGENTIAL PLANE

Figure 3 - Experimental Set-Up of Rake Calibration Equipment

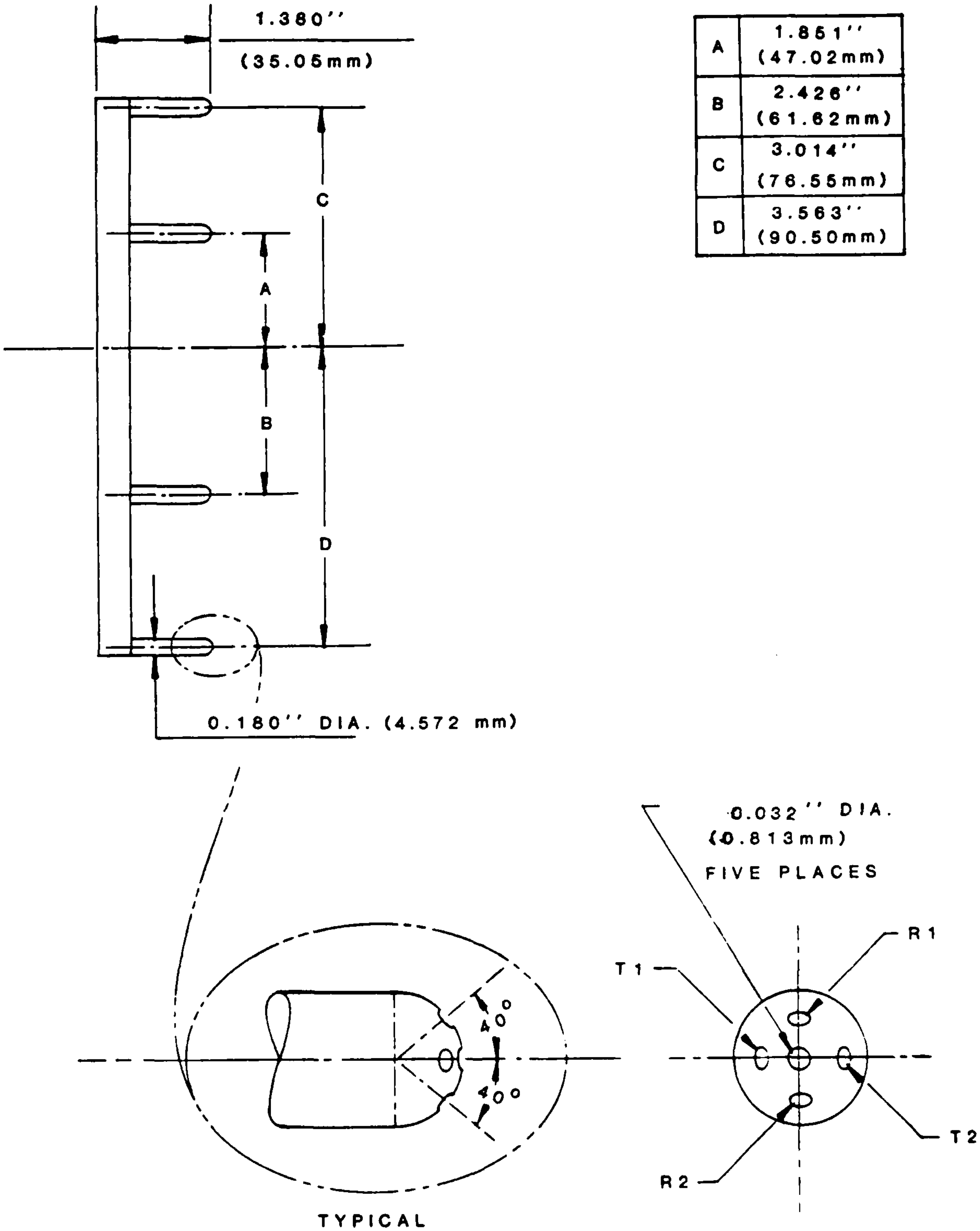

Figure 2 - Schematic of 5-Hole Pitot Tube Rake Arrangement

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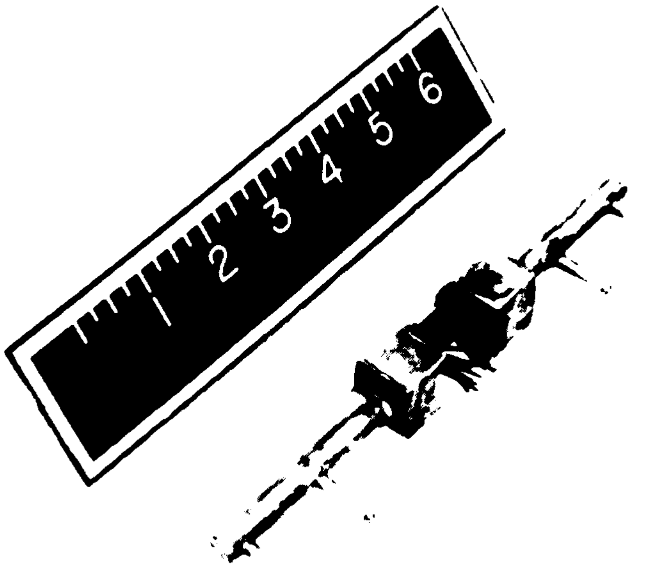

Figure 1 - Photograph of Rake 4

TABLE 1 - COEFFICIENTS FOR RAKE 4

$$Y = A0 + A1X + A2X^2 + A3X^3 + A4X^4$$

A0	A1	A2	A3	A4
0.257566E+01	0.205644E+02	-0.233292E+01	-0.206242E+01	0.567658E+00
0.100675E+00	0.562613E-02	-0.751480E-04	0.741833E-06	-0.264699E-07
0.244729E+01	0.209347E+02	0.346816E+01	-0.335986E+00	-0.113369E+00
0.129702E+00	-0.593296E-02	-0.758221E-04	-0.251349E-05	-0.889795E-07
0.710920E+01	0.205617E+02	-0.930594E+00	-0.404967E+01	0.137060E+01
0.696409E-01	0.517080E-02	0.814411E-05	-0.452851E-05	0.646135E-07
0.711550E+01	0.204345E+02	0.107765E+01	-0.108034E+01	-0.181500E+00
0.145589E+00	-0.552011E-02	-0.364840E-04	0.191087E-05	0.162763E-07
-0.147738E+01	0.202106E+02	-0.176001E+01	-0.142847E+01	0.321856E+00
0.126472E+00	0.637848E-02	0.361349E-05	-0.414126E-05	0.410027E-07
-0.152031E+01	0.206538E+02	0.284520E+01	-0.147418E+01	-0.409103E+00
0.109072E+00	-0.580049E-02	-0.106057E-03	-0.987561E-06	-0.206420E-07
0.407138E+01	0.215319E+02	0.136348E+00	-0.432153E+01	0.120072E+01
0.895742E-01	0.440392E-02	0.142800E-03	-0.111976E-04	0.167437E-06
0.405301E+01	0.216666E+02	0.147746E+01	-0.179939E+01	-0.391385E+00
0.131661E+00	-0.529097E-02	-0.766025E-04	-0.506452E-06	-0.204283E-07
0.213966E+01	0.216617E+02	0.268343E+01	-0.707823E+01	0.195748E+01
0.124880E+00	0.576810E-02	0.715526E-04	-0.888444E-05	0.137685E-06
0.203569E+01	0.225826E+02	0.391962E+01	-0.797354E+00	-0.252532E+00
0.152104E+00	-0.636761E-02	-0.138360E-03	-0.250877E-05	-0.549889E-07
0.545507E+01	0.210679E+02	0.347292E+01	-0.822357E+01	0.241400E+01
0.954338E-01	0.721993E-02	-0.671227E-05	-0.917694E-05	0.171346E-06
0.557710E+01	0.210330E+02	-0.346874E+01	-0.493156E+01	-0.992985E+00
0.167499E+00	-0.564793E-02	-0.860092E-04	0.103210E-06	-0.365895E-08
-0.151432E+01	0.224893E+02	-0.487010E+01	-0.164476E+00	0.145038E+00
0.142049E+00	0.614324E-02	-0.180899E-04	-0.622327E-05	0.109765E-06
-0.154261E+01	0.220203E+02	0.779363E+00	-0.327442E+01	-0.859239E+00
0.123429E+00	-0.590082E-02	0.615272E-04	0.892811E-05	0.145880E-06
0.263605E+01	0.238476E+02	-0.190558E+01	-0.353054E+01	0.106565E+01
0.120382E+00	0.522320E-02	0.895694E-04	-0.114912E-04	0.197350E-06
0.264796E+01	0.235508E+02	0.160953E+01	-0.245414E+01	-0.605401E+00
0.150539E+00	-0.600799E-02	-0.323373E-04	0.558154E-05	0.116724E-06

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APPENDIX A

PROCEDURE FOR DERIVING VELOCITY COMPONENT RATIOS FROM PRESSURE MEASUREMENTS

Column	Identification	Derivation
1	C-T1	Pressure at hole C minus pressure at hole T1, converted to inches of water pressure.
2	C-T2	Pressure at hole C minus pressure at hole T2, converted to inches of water pressure.
3	T2-T1	$= (C-T1) - (C-T2) =$ Col. 1 - Col. 2
4	2C-T2-T1	$= (C-T1) + (C-T2) =$ Col. 1 + Col. 2
5	$\frac{T2-T1}{2C-T2-T1}$	$= \frac{(C-T1) - (C-T2)}{(C-T1) + (C-T2)} =$ Col. 3 / Col. 4
6	β_{LT}	Angle of water flow in the LT plane. Read from calibration curve at value of $\frac{T2-T1}{2C-T2-T1}$ in Col. 5. If the value of Col. 5 is negative, read the curve labeled $\frac{T1-T2}{2C-T1-T2}$.
7	$\frac{C-T1}{V_{LT}^2}$	Read from calibration curve at value of β_{LT} in Col. 6, if the value of Col. 5 is positive. Otherwise, omit.
8	$\frac{C-T2}{V_{LT}^2}$	Read from calibration curve at value of β_{LT} in Col. 6, if the value of Col. 5 is negative. Otherwise, omit.
9	V_{LT}^2	$= \frac{C-T1}{(C-T1)/(V_{LT}^2)} =$ Col. 1 / Col. 7 if Col. 5 is positive, or $= \frac{C-T2}{(C-T2)/(V_{LT}^2)} =$ Col. 2 / Col. 8 if Col. 5 is negative.
10	V_{LT}	Component of the water velocity in the LT plane. $= \sqrt{V_{LT}^2} =$ square root of Col. 9.
11	$\cos \beta_{LT}$	= cos of angle in Col. 6.

Column	Identification	Derivation
12	$\sin \beta_{LT}$	= sin of angle in Col. 6.
13	V_{L_1}	Longitudinal component of the water velocity derived from V_{LT}. $= V_{LT} \times \cos \beta_{LT}$ = Col. 10 x Col. 11.
14	V_T	Tangential component of the water velocity. $= V_{LT} \times \sin \beta_{LT}$ = Col. 10 x Col. 12.
15	C-R1	Pressure at hole C minus pressure at hole R1, converted to inches of water pressure.
16	C-R2	Pressure at hole C minus pressure at hole R2, converted to inches of water pressure.
17	R2-R1	= (C-R1) - (C-R2) = Col. 15 - Col. 16
18	2C-R2-R1	= (C-R1) + (C-R2) = Col. 15 + Col. 16
19	$\frac{R2-R1}{2C-R2-R1}$	$= \frac{(C-R1) - (C-R2)}{(C-R1) + (C-R2)}$ = Col. 17 / Col. 18
20	β_{LR}	Angle of water flow in the LR plane. Read from calibration curve at value of $\frac{R2-R1}{2C-R2-R1}$ in Col. 19. If the value of Col. 19 is negative, read the curve labeled $\frac{R1-R2}{2C-R1-R2}$
21	$\frac{C-R1}{V_{LT}^2}$	Read from calibration curve at value of β_{LR} in Col. 20, if the value of Col. 19 is positive. Otherwise, omit.
22	$\frac{C-R2}{V_{LT}^2}$	Read from calibration curve at value of β_{LR} in Col. 20, if the value of Col. 19 is negative. Otherwise, omit.
23	V_{LR}^2	$= \frac{C-R1}{(C-R1)/(V_{LR}^2)}$ = Col. 15 / Col. 21 if Col. 19 is positive, or $= \frac{C-R2}{(C-R2)/(V_{LR}^2)}$ = Col. 16 / Col. 22 if Col. 19 is negative.

Column	Identification	Derivation
24	V_{LR}	Component of the water velocity in the LR plane $= \sqrt{V_{LR}^2}$ = square root of Col. 23.
25	$\cos \beta_{LR}$	= cos of angle in Col. 20.
26	$\sin \beta_{LR}$	= sin of angle in Col. 20.
27	V_{L_2}	Longitudinal component of the water velocity derived from V_{LR}. $= V_{LR} \times \cos \beta_{LR}$ = Col. 24 x Col. 25.
28	V_R	Radial component of the water velocity. $= V_{LR} \times \sin \beta_{LR}$ = Col 24 x Col. 26.
29	V	Model speed in ft/sec.
30	V_X/V	Longitudinal component of the water velocity expressed as a ratio of ship speed. $= 1/2 \ (V_{L_1} + V_{L_2}) \ / \ V$ = (Col. 13 + Col. 27) / (2 x Col. 29)
31	V_T/V	Tangential component of the water velocity expressed as a ratio of ship speed. = Col. 14 / Col. 29
32	V_R/V	Radial component of the water velocity expressed as a ratio of ship speed. = Col. 28 / Col. 29

V_X/V is positive in the aft direction.

V_T/V is positive in the counterclockwise direction.

V_R/V is positive toward the shaft centerline.

r/R and Θ are the polar coordinates of the point in the TR plane at which the wake is measured. r is the radial distance of the point from the centerline of the propeller shaft; R is the design propeller radius. Θ is the position angle measured from the top of the propeller disc in a counterclockwise direction.

CALCULATION OF WAKE SURVEY DATA OBTAINED WITH PITOT TUBE RAKE NO._______ MODEL________ TEST______

Col.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	NO.	r/R	θ	Pitot Tube
No.	C−T1	C−T2	T2−T1	2C−T2−T1	$\frac{T2-T1}{2C-T2-T1}$	β_{LT}	$\frac{C-T1}{V_{LT}^2}$	$\frac{C-T2}{V_{LT}^2}$	V_{LT}^2	V_{LT}	$\cos\beta_{LT}$	$\sin\beta_{LT}$	V_{L1}	V_T				
1															1			
2															2			
3															3			
4															4			
5															5			
6															6			
7															7			
8															8			
9															9			
1C															10			

Col	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
No	C-R1	C-R2	R2-R1	2C-R2-R1	$\frac{R2-R1}{2C-R2-R1}$	β_{LR}	$\frac{C-R1}{V_{LR}^2}$	$\frac{C-R2}{V_{LR}^2}$	V_{LR}^2	V_{LR}	$\cos\beta_{LR}$	$\sin\beta_{LR}$	V_{L_2}	V_R	V	V_X/V	V_T/V	V_R/V
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		

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APPENDIX B

CALIBRATION CONSTANTS

I. FORM OF CALIBRATION EQUATION

$$Y = A_1 + A_2X + A_3X^2 + A_4X^3 + A_5X^4$$

II. CALIBRATION CURVE LABELS FOR THE HORIZONTAL/TANGENTIAL PLANE

Curve Number	X	Y
1	$\frac{T_2 - T_1}{2C - T_2 - T_1}$	β
2	β	$\frac{C - T_1}{V^2}$
3	$\frac{T_1 - T_2}{2C - T_1 - T_2}$	β
4	β	$\frac{C - T_2}{V^2}$

III. CALIBRATION CURVE LABELS FOR THE VERTICAL/RADIAL PLANE

Curve Number	X	Y
5	$\frac{R_2 - R_1}{2C - R_2 - R_1}$	β
6	β	$\frac{C - R_1}{V^2}$
7	$\frac{R_1 - R_2}{2C - R_1 - R_2}$	β
8	β	$\frac{C - R_2}{V^2}$

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